Advanced Computer Graphics (Fall 2009)

CS 294, Rendering Lecture 11

Representations of Visual Appearance

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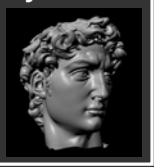
Realistic Rendering

Geometry



Rendering Algorithm

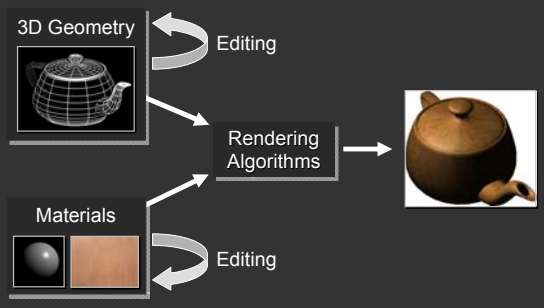
Arnold Renderer: Marcos Fajardo

Materials/Lighting

Texture Reflectance [BRDF] Lighting

Realistic Input Models Required

Production Pipeline



Traditional Computer Graphics

Directional

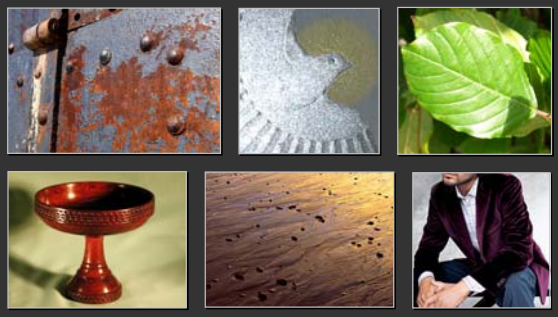
Parametric Scattering Functions

Spatial

Hand Painted Texture Maps

Traditional Computer Graphics

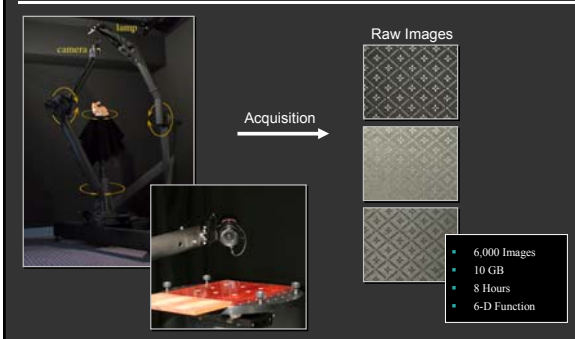
Appearance in the Real World



Motivation

- Have reached the limit of simple parametric reflectance (or animation, geometric models)
- Input appearance models, not Algorithms for rendering are limiting factor in realism
- Improvements require data-driven models

Data-Driven Appearance Models



Stanford/Cornell Graphics Labs

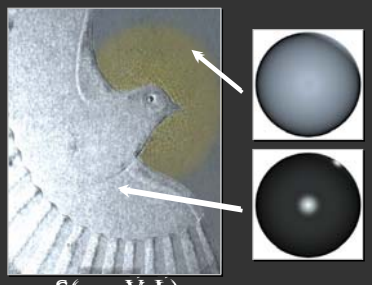
Lawrence *et al.* 06

Motivation

- Have reached the limit of simple parametric reflectance (or animation, geometric models)
- Input appearance models, not Algorithms for rendering are limiting factor in realism
- Improvements require data-driven models
- ***Measure real-world visual appearance and represent***
  - What types of datasets to measure or acquire?
  - What mathematical representations to use?

The SVBRDF

Spatially
Varying
Bi-Directional
Reflectance
Distribution
Function



$S(u, v, \vec{V}, \vec{L})$

General Problem Characterization

6D Spatially-Varying Reflectance (SVBRDF)

- Lighting direction (2D)
- Viewing direction (2D)
- Spatial location (2D)

With ~ 100 samples per dimension

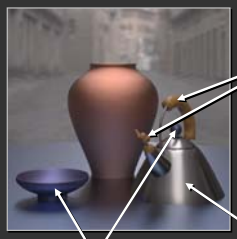
- ~ 10^{12} samples total!!
- Intractable representation, rendering

Need usable compact representations that enable

- Interactive rendering
- Global illumination (offline) rendering
- Editing

Interactive Rendering

Global Illumination



Measured Plastic

Measured Metallic-Blue Paint

Measured Nickel

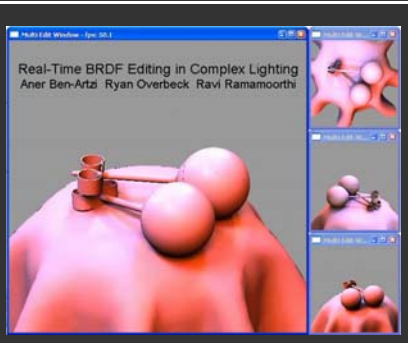
Lawrence *et al.* 04

Editing

Original Image

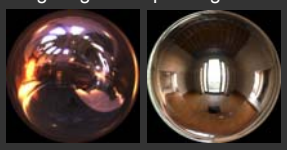
Adjust Material Properties

BRDF Editing in Complex Lighting



Types of Measured Visual Appearance

- Lighting: From point lights to environment maps and beyond

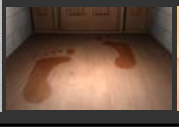


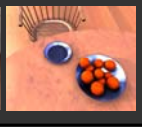
Grace Cathedral and Kitchen light probes
Courtesy Paul Debevec www.debevec.org

- BRDFs: From Lambertian/Cook Torrance to measured/factored

Types of Measured Visual Appearance

- "Reflectance Fields": Variation with lighting and/or view
- Subsurface and Volumetric Scattering
- Time-Varying Surface Appearance
- BTFs or Bi-Directional Texture Functions
- And many more (full taxonomy later)





Time-Varying Appearance: Video

The Challenge

6D Spatially-Varying Reflectance (SVBRDF)

- Lighting direction (2D)
- Viewing direction (2D)
- Spatial location (2D)

With ~ 100 samples per dimension

- ~ 10^{12} samples total!!
- Intractable representation, rendering

Other functions can be even higher dimensional

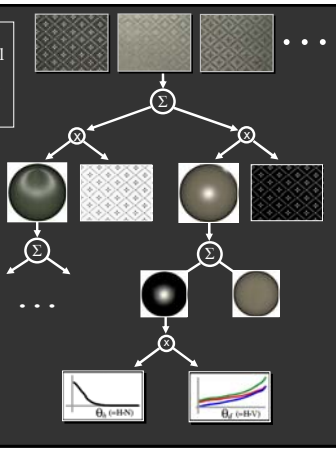
Mathematical Representations

How to address the curse of dimensionality, complexity?

- Low-frequency spherical harmonic descriptions
- Factorization into lower-dimensional components
- Sparse wavelet representations

- Nonlinear factorizations and machine learning
- Clustered low-dimensional subspaces
- Radial basis function approximations
- First order or gradient analysis
- And many more…

Contribution #1:
Represent high-dimensional measured function as tree-structured collection of simple parts.



Contribution #1:
Represent high-dimensional measured function as tree-structured collection of simple parts.

Contribution #2:
Each level in tree computed as matrix factorization.

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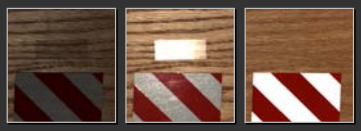
Represent high-dimensional measured function as tree-structured collection of simple parts.

Contribution #2:
Each level in tree computed as matrix factorization.

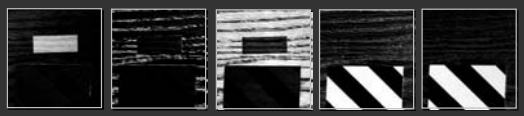
Contribution #3:
Intuitive decomposition achieved using constrained factorization.

Wood + Tape Dataset

Wood + Tape Dataset

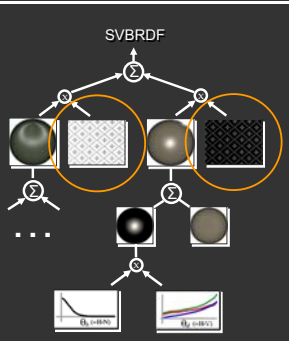


Blending Weights Computed with ACLS (5 Terms)



Scotch Tape | Dark Wood Grain | Light Wood Grain | Red Bicycle Tape | White Bicycle Tape

Data-Driven Editing: Spatial Texture

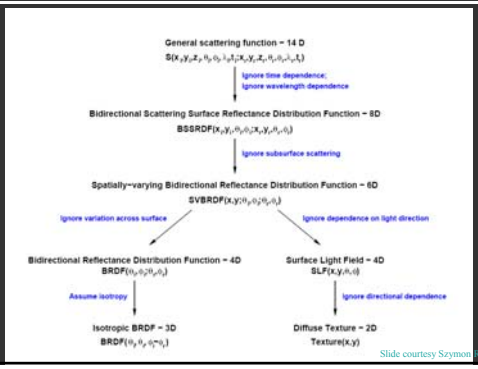


Video

Historical Overview

- 1980-95: Focus on parametric reflectance models, fast offline finite element and Monte Carlo rendering algorithms
- Circa 1995: Focus shifts to input appearance models. Measured BRDFs and image-based rendering prominent
- 1998- : Strong interest in data-driven appearance. But these are gigantic datasets. Focus: efficiently represent
- 2002- : Relevant even for purely synthetic real-time rendering: Precompute data-driven models, represent efficiently
- Great deal of current work on acquiring and representing realistic lighting, materials…

Taxonomy of Appearance



Slide courtesy Szymon Rusinkiewicz

General Plenoptic Function

- All knowledge of light in scene [Adelson 91]
- Anywhere in space (x, y, z)
- In any direction (θ, ϕ)
- At any time instant (t)
- For any wavelength of light (λ)
- Function of 7 variables, therefore 7D function
- We care about taxonomy of *scattering functions*
  - *General Scattering Function is 14D (bet. two plenoptics)*

$$f(x_i, y_i, z_i, \theta_i, \phi_i, \lambda_i, t_i\ ;\ x_o, y_o, z_o, \theta_o, \phi_o, \lambda_o, t_o)$$

Common Assumptions

- Ignore time dependence (no phosphorescence or time-varying BRDF properties [but see my work on T(S)VBRDFs])
- Ignore wavelength (no fluorescence, assume RGB)
- Travel in free space, parameterize on surfaces (no z)
  - Alternative for light fields: 4D space of rays (intersections in 2 planes)
- Each of these removes 1D of plenoptic, 2D of scattering
- Left with 8D function of greatest importance for class
- 8D Bi-Directional Surface Scattering Distribution Function (BSSRDF) $f(x_i, y_i, \theta_i, \phi_i; x_o, y_o, \theta_o, \phi_o)$

Taxonomy of 8D Scattering Function

$$f(\vec{x}_i,\vec{\omega}_i\,;\vec{x}_o,\vec{\omega}_o)$$

- Function of two spatial positions, two spherical angles (4 total)
- Can consider any subsets of 1-4 of these
  - Slices of the full 8D BSSRDF
- Number of possible slices is 4+6+4+1 = 15.
  - Not all make sense, but most do and have begun to be studied
- ***Unified framework not readily known, presented in lecture***

6D Scattering Functions 1

$$f(\vec{x}_i,\vec{\omega}_i\,;\vec{x}_o,\vec{\omega}_o)$$

Ignore subsurface scattering

$$\vec{x}_i = \vec{x}_o = \vec{x}$$

$$f(\vec{x},\vec{\omega}_i,\vec{\omega}_o)$$

SVBRDF Lawrence 06

Spatially-Varying BRDF (6D SVBRDF)
BiDirectional Texture Function (6D BTF)
Also, for relighting image, changing view

CURET: Corduroy BTF

"Other" Functions (slices not open to easy interpretation).
See if you can find a good interpretation (briefly discuss later)

$f(\vec{x}_i;\vec{x}_o,\vec{\omega}_o)$ $f(\vec{\omega}_i\,;\vec{x}_o,\vec{\omega}_o)$ $f(\vec{x}_i,\vec{\omega}_i\,;\vec{x}_o)$ $f(\vec{x}_i,\vec{\omega}_i\,;\vec{\omega}_o)$

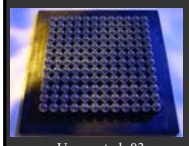
4D "Scattering" Functions 1

$$f(\vec{x},\vec{\omega}_i,\vec{\omega}_o)$$

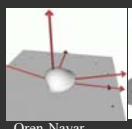
$f(\vec{x},\vec{\omega}_i)$ Incident Light Field

$f(\vec{\omega}_i,\vec{\omega}_o)$ 4D BRDF BiDirectional Reflectance Distribution Function

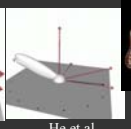
$f(\vec{x},\vec{\omega}_o)$ Surface Light Field



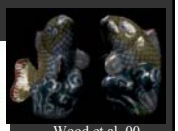
Unger et al. 03



Oren-Nayar



He et al.



Wood et al. 00

From Oregon BRDF Library

2D Functions 1

4D $f(\vec{x},\vec{\omega}_i)$ Incident Light Field

$f(\vec{\omega}_i,\vec{\omega}_o)$ BRDF

$f(\vec{x},\vec{\omega}_o)$ Surface Light Field

2D $f(\vec{\omega}_i)$ Incident Illumination Environment Map

$f(\vec{x})$ Texture Map

$f(\vec{\omega}_o)$ Outgoing Illumination "Lumisphere"

Complete Branch of Taxonomy

8D $f(\vec{x}_i,\vec{\omega}_i\,;\vec{x}_o,\vec{\omega}_o)$

Ignore subsurface scattering

$$\vec{x}_i = \vec{x}_o = \vec{x}$$

6D $f(\vec{x},\vec{\omega}_i,\vec{\omega}_o)$

4D $f(\vec{x},\vec{\omega}_i)$ Incident Light Field

$f(\vec{\omega}_i,\vec{\omega}_o)$ BRDF

$f(\vec{x},\vec{\omega}_o)$ Surface Light Field

2D $f(\vec{\omega}_i)$ Incident Illumination Environment Map

$f(\vec{x})$ Texture Map

$f(\vec{\omega}_o)$ Outgoing Illumination "Lumisphere"

Taxonomy of 8D Scattering Function 1

$$f(\vec{x}_i,\vec{\omega}_i\,;\vec{x}_o,\vec{\omega}_o)$$

- Function of two spatial positions, two spherical angles (4 total)
- Can consider any subsets of 1-4 of these
  - Slices of the full 8D BSSRDF
- Number of possible slices is 4+6+4+1 = 15.
  - Not all make sense, but most do and have begun to be studied
- ***One (main) branch of this taxonomy seen so far***
  - ***A total of 8 slices (1+1+3+3)***
  - ***Now, proceed to consider other (more exotic) possibilities***

6D Scattering Functions 2

$f(\vec{x}_i,\vec{\omega}_i\,;\vec{x}_o,\vec{\omega}_o)$

↓

$f(\vec{x}_i,\vec{\omega}_i;\vec{x}_o)$

Relighting images with 4D Incident Light Fields

Not studied (what it means?)

$f(\vec{x}_i;\vec{x}_o,\vec{\omega}_o)$

Considered in SVBRDF

$f(\vec{\omega}_i\,;\vec{x}_o,\vec{\omega}_o)$

$f(\vec{x}_i,\vec{\omega}_i\,;\vec{\omega}_o)$

Masselus et al. 03

4D Scattering Functions 2

$f(\vec{x}_i,\vec{\omega}_i\,;\vec{x}_o,\vec{\omega}_o)$

↓

$f(\vec{x}_i,\vec{\omega}_i;\vec{x}_o)$

Relighting images with 4D Incident Light Fields

Ignore angular dependence ↓

$f(\vec{x}_i;\vec{x}_o)$

Suburface Scattering

Peers et al. 06

Image relighting (distant illum.)

$f(\vec{\omega}_i\,;\vec{x}_o)$

Incident Light Field (already seen)

$f(\vec{x}_i,\vec{\omega}_i)$

Taxonomy of 8D Scattering Function 1

$f(\vec{x}_i,\vec{\omega}_i\,;\vec{x}_o,\vec{\omega}_o)$

- Function of two spatial positions, two spherical angles (4 total)
- Can consider any subsets of 1-4 of these
  - Slices of the full 8D BSSRDF
- Number of possible slices is ***4+6+4+1 = 15***.
  - Not all make sense, but most do and have begun to be studied
- One (main) branch of this taxonomy
  - A total of 8 slices (1+1+3+3)
- Second branch of taxonomy
  - Relighting, incl. with incident light fields, subsurface scattering
  - 3 additional slices (0+1+2+0). ***Total 11 (what happened others?)***

Review of 8D and 6D

$f(\vec{x}_i,\vec{\omega}_i\,;\vec{x}_o,\vec{\omega}_o)$

- 1 slice at 8D, 4 possible slices in 6D (drop any variable)
- We have seen only 2 possible slices. What happened others?
- Either remove a spatial dimension (1 slice)
  - Spatially varying BRDFs (spatial incident = outgoing)
  - Only 1 slice, not the two expected
- Or remove an angular dimension (1 slice)
  - Relighting with incident light fields
  - No easy interpretation for $f(\vec{x}_i\,;\vec{x}_o,\vec{\omega}_o)$

Review of 4D

$f(\vec{x}_i,\vec{\omega}_i\,;\vec{x}_o,\vec{\omega}_o)$

- 6 possible 4D slices (choose 2 variables out of 4)
- Seen 3 of these in main branch (from 6D SVBRDF)
  - BRDF
  - Incident Light Field
  - Surface Light Field
- Another 2 in second branch
  - Subsurface scattering (heterogeneous)
  - Relighting
- Only 5 of the 6 slices studied
  - No easy interpretation for $f(\vec{x}_i;\vec{\omega}_o)$

Review of 2D

$f(\vec{x}_i,\vec{\omega}_i\,;\vec{x}_o,\vec{\omega}_o)$

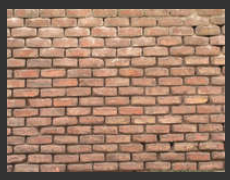
- 4 possible 4D slices (chose 1 variable out of 4)
- Seen 3 of these in main branch (from 6D SVBRDF)
  - Diffuse texture (only 1 slice)
  - Incoming environment map
  - Outgoing lumisphere

Historical Timeline

- Built up from 2D to 4D to 6D to 8D functions
  - 2D functions (texture, env maps) known since 1975-80
  - 4D functions (light fields) in 1996 catalyzed revolution
  - 6D functions (CURET 1999, Incident LF 2003)
  - 8D functions 2006, first acquisitions of full transport
- Generally, individual papers on each topic
- General framework and theory only now emerging

Historical Timeline: Details 2D

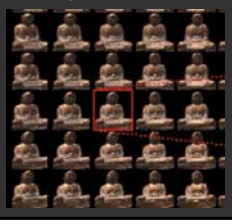
- Texture Maps [Catmull 1974]
- Environment Maps [Blinn 76, Miller & Hoffmann 84]




- "Lumispheres" not much work on alone (most in context of surface light fields, relighting)

Historical Timeline: Details 4D

- BRDFs have a long history (70^s – 80^s), but work on measuring them is accelerating in last 10 years
- Light Field Rendering / Lumigraph
  - Levoy and Hanrahan 96 ; Gortler et al. 96




Historical Timeline: Details 4D

- BRDFs have a long history (70^s – 80^s), but work on measuring them is accelerating in last 10 years
- Light Fields and more general 4D functions
  - Reflectance fields (relighting faces) Debevec et al. 00
  - Surface Light Fields (Wood et al. 00 ; Nishino et al. 99)
  - Incident Light Fields (Unger et al. 03 ; Goesele et al. 03)
  - Heterogeneous Subsurface Scattering (Peers et al. 06)

Historical Timeline: Details 6D

- Spatially varying BRDFs have long history but dense measurement previously impossible
  - Now BTF (CURET 99), Factored forms (Lawrence 06) etc.

- 6,000 Images
- 10 GB
- 8 Hours
- 6-D Function

Lawrence *et al.* 06

Historical Timeline: Details 6D

- Spatially varying BRDFs have long history but dense measurement previously impossible
  - Now BTF (CURET 99), Factored forms (Lawrence 06) etc.
- Relighting with Incident Light Fields
  - Masselus et al. 03
  - Dual Photography: Sen et al. 05

The holy grail of 8D

- Complete light transport of a complex scene
- No complete solutions yet, but first papers have appeared (Garg et al. 06)
- At this point, all 11 functions in taxonomy have had at least the first paper on them (although there is still much to do)